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Numerical study on double injection techniques in a gasoline and biodiesel fueled RCCI (reactivity controlled compression ignition) engine

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HIGHLIGHTS

- Double injection strategy is applied to RCCI engine.
- The 2nd SOI timing is a crucial parameter to characterizing the combustion process.
- Either short (5 °C) or long dwell (35 °C) could lower the peak pressure rise rate.
- Adopting short dwell (5 °C) could mitigate the formation of NO and soot emissions.

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ABSTRACT

In an RCCI (reactivity controlled compression ignition) engine, the double injection strategy is a technical tool to control its combustion process. In this study, the effects of two key injection parameters, namely dwell and split fraction, are numerically investigated in a gasoline and biodiesel fueled RCCI engine. In the engine, gasoline is used as the premixed fuel; meanwhile, biodiesel is directly injected into the air-fuel mixture. The coupled KIVA4-CHEMKIN code was used to simulate the in-cylinder combustion process and the emissions formation. The gasoline/biodiesel reaction mechanism, which consists of 107 species and 425 reactions, was implemented in the code for detailed chemistry calculation. During the simulation, the dwells between 1st and 2nd SOI (start of injection) timings were varied at 5, 15, 25 and 35°CA, while the 1st SOI timing was fixed at −35 °C ATDC. Besides, the 1st pulse fractions were changed at 30%, 50% and 70%; accordingly, the rest of the biodiesel was injected through the 2nd pulse. The combustion characteristics (including in-cylinder pressure, HRR (heat release rate), ignition delay, PPRR (peak pressure rise rate) and combustion duration), engine performance and emissions (NO and soot) formations were compared under various operating conditions. The results show that double injection strategy results in longer ignition delay. In contrast with the dwells of 15° and 25°CA, the cases with dwells of 5° and 35°CA could result in acceptable PPRR, longer combustion duration, but slightly lower IMEP (indicated mean effective pressure). However, short dwell of 5°CA displays better results on NO and soot emissions. The combustion process with long dwell of 35°CA is both reactivity and mixing controlled.

1. Introduction

It is known that CDC (Conventional Diesel Combustion) emits high NOx and soot emissions due to the combustion characteristics of diffusion flame. In addition, between NOx and soot, there exists a trade-off relationship. To resolve this dilemma, the LTC (Low Temperature Combustion), including HCCI (Homogeneous Charge Compression Ignition), PCCI (Premixed Charge Compression Ignition) and RCCI (Reactivity-controlled compression ignition), etc., has become attractive [1]. Studies have shown that LTC is an effective way of reducing NOx and soot emissions simultaneously. Among the LTC regimes, RCCI has drawn much attention because it is capable of achieving wider ranges of loads by moderating the fuel fractions and the injection strategies [2]. The superiority of RCCI is the involvement of two types

Abbreviations: ATDC, after top dead center; CA, crank angle; CA5, crank angle of 5% heat released; CA50, crank angle of 50% heat released; CA90, crank angle of 90% heat released; CDC, conventional diesel combustion; EFC, evaporative fuel consumption; EVO, exhaust valve open; HCCI, homogeneous charge compression ignition; HRR, heat release rate; IMEP, indicated mean effective pressure; IVC, intake valve close; KH, Kelvin-Helmholtz; LTC, low temperature combustion; MD, methyl-decenoate; MD9D, methyl-9-decenoate; NO, nitrogen monoxide; NO_x, nitrogen oxides; PCCI, premixed charge compression ignition; PM, particulate matter; RCCI, reactivity controlled compression ignition; PPRR, peak pressure rise rate; rpm, revolution per minute; RNG, re-normalization group; RT, Rayleigh-Taylor; SOI, start of injection; TDC, top dead center; UHC, unburned hydrocarbon

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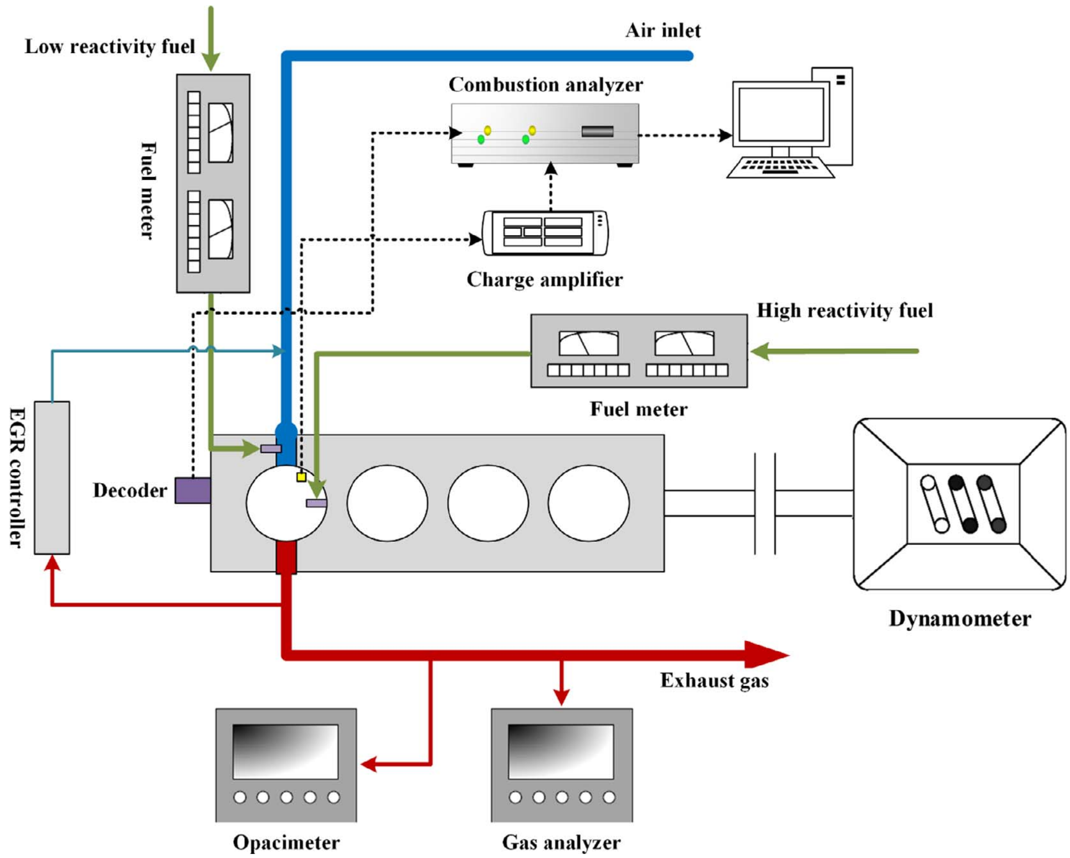

Fig. 1. Schematic diagram of the engine test bed.

Table 1
Modified dual-fuel engine specifications.

Type	Dual fuel engine
Prototype	GW4D20 diesel engine
Bore (mm)	83.1
Stroke (mm)	92
Displacement (L)	0.5
Compression Ratio	16.7
Biodiesel injection pressure (MPa)	40–180
Gasoline injection pressure (MPa)	0.2–0.3
Number of injector holes	7
Intake valve close (°C ATDC)	−130
Exhaust valve open (°C ATDC)	94
Swirl ratio	1.7

Table 2
Properties of fuels tested in the modified single-cylinder engine.

	Gasoline	Biodiesel (palm oil methyl ester)
Lower heating value (MJ/kg)	43.50	38.29
Cetane number	–	61.7
Research Octane number	94.0	–
Viscosity @ 20 °C (mm^2/s)	–	7.159
Liquid density @ 20 °C (kg/m^3)	753.0	871.4

of fuels which in turn enable the adjustment of in-cylinder fuel reactivity gradient [3]. Thus, researchers have put much effort into the studies of injection parameters of fuels for the purpose of efficiency improvement and emissions reduction [4–6]. Some of the major injection parameters are premixed fuel ratio, injection pressure, direct-injected fuel spray angle and SOI (start of injection) timing, etc. [7,8], which are mostly related to the injection strategy of an engine.

In the past few years, investigations on SOI timings of RCCI engines were conducted under various conditions. Most of them adopted the single injection strategy. Benajes et al. [9] swept the SOI timings from −30° to −15 °C ATDC in a gasoline/diesel fueled RCCI. Results showed that the delay of SOI timing could decrease NOx and soot emissions but increase UHC and CO emissions. Wu and Reitz [10] conducted experiments on a gasoline/diesel fueled RCCI engine with the IMEP of 18 bar. The SOI timings were varied from −60° to 0 °C ATDC. By retarding the SOI timing, soot, UHC and CO firstly descended and then increased. On the contrary, NOx emissions firstly increased and then decreased. Moreover, the efficiency of the engine showed increasing trend first, followed by the dropping trend. Wang et al. [11] experimentally conducted the parametric study on the gasoline and diesel fueled RCCI engine. Among the investigated operational parameters, the diesel SOI timings were adjusted from −52° to −17 °C ATDC with different premixed gasoline ratios. Results indicated that advancing SOI timing could retard the combustion phasing, reduce NOx and soot, and extend the high load limit. Li et al. [12] investigated the effect of SOI timing (swept from −37° to −7 °C ATDC) in a methanol/diesel fueled RCCI engine. The decreasing trend was observed for NOx with the delay of SOI timing; in contrast, increasing trend was seen for both soot and UHC. Zhang et al. [13] investigated the effect of SOI timing in a n-butanol/n-heptane fueled RCCI engine. The results suggested that direct injection timing has significant effects on combustion phasing.

Compared to the single injection strategy, double injection strategy brings more flexibility because it involves more controllable parameters such as 1st and 2nd SOI timings and split injection fraction. Some investigations have been carried out on the comparison of single and double injection strategies. Splitter et al. [14] varied the 1st SOI timings of double injection from −145 to −35°CA ATDC with an identical dwell of 25° in an iso-octane and n-heptane fueled RCCI engine. Compared with the results of single injection strategy, double injection